SEAFICS: Seals and Fisheries Co-existing Sustainably

Assessment of acoustic exposure & presence of cetaceans around static-net fisheries equipped with targeted acoustic startle technology (TAST) to mitigate seal depredation

Final Report to National Parks and Wildlife Service (NPWS)
Grant ID: SPU G27-2021

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University College Cork, March 2024

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SUMMARY

Depredation, the full or part removal of fish from nets by seals, is a major source of conflict between fisheries and seals. In response to this, standard acoustic deterrent or harassment devices (ADDs & AHDs) have been used to reduce interactions between seals and fisheries, however habituation (particularly where food motivation is high), alongside hearing damage and habitat exclusion of non-target species such as cetaceans limit their use. In recent years, targeted acoustic startle technology (TAST) has been developed to address concerns. By eliciting a startle response mediated by an autonomous reflex arc in the brainstem, habituation by seals is prevented. Moreover, this approach only requires low noise doses, as it uses brief isolated sound signals emitted at low duty cycles (1-2% time sound is emitted) within a specific frequency band where seal hearing is more sensitive than that of non-target species (such as harbour porpoise). Together these features work to reduce noise exposure and minimise disturbance to non-target species and seals. Here, we provide results assessing noise emission and the potential for behavioural disturbance to cetaceans by a new TAST prototype, designed and supplied by GenusWave Ltd (www.genuswave.com), for use at static-net fisheries off South-West Ireland where seal-fishery interactions are perceived to be particularly high. Two boats fishing gillnets targeting pollock were procured to run control-test trials across normal fishing grounds around the Blasket Islands and larger Dingle Bay area in September/October 2023. Trials were run in net deployment sets of three (two control nets and one test net with the TAST prototype). SoundTraps were deployed on nets to assess cetacean presence. A total of 19 trial days of at-sea work and two nights of overnight deployments were completed between September 2022 and May 2023, yielding over 200 hours of acoustic recordings across 40 control and 18 test net deployments. Passive acoustic monitoring (PAM) of cetacean vocalisations was conducted, and sound propagation of the TAST signals was measured. The TAST signal characteristics were in line with factory calibration and received levels dropped off quickly with transmission loss being marginally higher than spherical spreading (20.2*log10 distance in metres), supporting general findings of a highly localised deterrence effect. Vocalisations of baleen whales were rare, with only a handful of encounters identified on a single day. Statistical modelling was conducted to estimate detection probabilities of cetacean vocalisation presence while also taking environmental and contextual variables into account. Delphinid vocalisations were encountered frequently during the study with best estimates for whistle detection probabilities of clicks ranging from ~ 27% to ~50% during the night and 8% during the day. Broadband click detections were slightly less common but still frequent with estimates ranging from ~38%- 40% during the night and ~5% during the day The statistical analysis showed that detection probabilities for both *delphinid* clicks and whistles were near identical during TAST on and off periods with models indicating no effect exerted by TAST operation. In contrast to the lack of a TAST effect there is evidence for detection delphinid vocalisations rates being higher at night than during the day. Harbour porpoise detections were more common than baleen whales, but overall rare (< 1%) and much less frequent than delphinids. While we found no evidence for differences in porpoise detection probabilities with TAST operation/presence, no definitive conclusions can be drawn due to low sample size. We discuss the possibility of population trends and/or inter-species interactions (i.e. presence of bottlenose dolphins) causing the generally low detection likelihoods of porpoise in this study. We also make suggestions that regulatory frameworks consider options to use combined (TAST) devices that prevent lethal bycatch of delphinids and porpoise, while also preventing depredation by phocid seals.

1. INTRODUCTION

Depredation (the full or part removal of fish from nets) by seals, is a major source of conflict between fisheries and seals (Cronin et al. 2014). The issue is two-fold, having both socio-economic and conservation implications. Fishers suffer economic losses through loss of catch and/or damage to gear (Cosgrove et al. 2015), alongside time spent disentangling damaged fish and/or by-caught seals (Cosgrove et al. 2015 & 2016). In tandem, by-catch mortality is one of the biggest anthropogenic threats to marine mammal populations (Read et al. 2006). Moreover, fishers may shoot seals visible around nets (either authorised or illegally; Journal News Source 2012, Nunny et al. 2018). The ecological impacts of long-term behavioural changes by seals reliant on such artificial resources is also of concern (Wilson et al. 2020). These interactions and their impacts are most prominent in static-net fisheries including gill, tangle, and trammel nets (Cronin et al. 2014, Read et al. 2006).

In Ireland, past reports suggest the perceived rate and impact of seal depredation is increasing across the south-west/west of the country (Cronin et al. 2014), which although not directly linked, has coincided with local increases in populations of grey and harbour seals (Duck & Morris 2012, O'Cadhla et al. 2013). Problems have been most accentuated in small-scale coastal/inshore fisheries targeting species such as pollack, monkfish and hake, such that some have been partially or fully abandoned (Cronin et al. 2014, Skipper News Source 2020). Recent renewed calls from the fishing industry for the state to provide solutions reflect an escalation in conflicts, and include appeals for a seal cull (RTE News Source 2020). This is problematic given the protected status of seals under both Irish (Irish Wildlife Act, 1976) and European (The EU's Marine Mammal Protection Act, 1972) law, and seals being listed under Annex II of the Habitats Directive (Council Directive: 92/43/EEC) requiring populations to be maintained at favourable levels. There is also a lack of evidence that such actions would be effective (Bowen & Lidgard 2013), whilst seals play a vital role in ecosystem dynamics (Heithaus et al. 2008) and are an engaging animal with strong public support (Bowen & Lidgard 2013), making population control measures particularly controversial. Nonetheless, a lack of action has led some fishers to take matters into their own hands, with reports of illegal culls (Journal News Source 2012). An effective and pragmatic solution is urgently required.

In the past, acoustic deterrent or harassment devices (ADDs & AHDs) have been used to reduce interactions between seals and fisheries (Götz & Janik 2013, Cosgrove et al. 2015). Conventional ADDs & AHDs work by emitting a loud and/or painful noise stimulus from an underwater speaker that causes seals to avoid or leave an area. However, habituation through time has been reported where food motivation is high (rendering devices ineffective for long term use; Gotz & Janik 2013). Moreover, ADDs & AHDs can induce habitat exclusion (Götz & Janik 2013, Findlay et al. 2024) alongside hearing damage in non-targeted species, such as odontocetes, especially if exposure times are long (as often required) and the responsiveness of impacted animals low (Götz & Janik 2013). In recent years, several analyses have highlighted the cumulative impacts of their widespread use (Findlay et al. 2018, 2022). In Europe, many of these species are listed under Annex II of the Habitats Directive (Council Directive: 92/43/EEC), and following Article 12 of the Habitat Directive, are afforded protection. Member states are obligated to monitor/research instances where accidental disturbance, and/or capture or killing may occur, such that appropriate conservation measures can be implemented.

In recent years, targeted acoustic startle technology (TAST) has been developed to address the operational and conservation concerns of ADDs and AHDs. By eliciting a startle response mediated by an autonomous reflex arc in the brainstem, habituation by seals can be prevented (Götz & Janik 2011). Moreover, this approach only requires low noise doses, and uses brief isolated sound signals emitted at low duty cycles (% time sound is emitted – can be as low as 1-2%). In addition, a specific frequency band is targeted where seal hearing is much more sensitive than that of non-target species (such as the harbour porpoise; Götz & Janik 2015). Together these features work to reduce noise exposure and minimise disturbance to non-target species and seals. TAST has been found successful at keeping seals away from fish farms in Scotland, reducing predation by 91-97% whilst not adversely impacting non-target species over long (~ 1 year) deployments (Gotz & Janik 2015 & 2016).

Here, we provide results assessing noise emission and the potential for behavioural disturbance to cetaceans by a new TAST prototype (thereafter 'the TAST'), designed and supplied by GenusWave Ltd (www.genuswave.com), for use at static-net fisheries off South-West Ireland, where seal-fishery interactions are perceived to be highest.

Figure 1. The TAST prototype (GenusWave Ltd), versions 1 (left) and 2 (right, with improved ergonomic design based on feedback from fishers to engineers at GenusWave Ltd), used in trials. The watertight housing (stainless steel) measures ~60 cm in length and ~20 cm in diameter, with a total weight of water of around 12 kg. It is pressure compensated and suitable for deployments down to around 100 m depth.

2. METHODS

2.1 Fieldwork

Two boats were procured via the Marine Institute under Framework Tender ITT21-019 (lot 2, mini-competition 7, contact person Dr Oliver Tully; funded by the European Maritime, Fisheries, and Aquaculture Fund (EMFAF) Marine Biodiversity Scheme at the Marine Institute) to run trials testing the TAST devices over 20 days (10 days each). While boats are licensed for use with multiple gear and on several target species, they generally fish pollock using static gill-nets and crayfish using tangle-nets. The Realt na Mara (code/registration C175) is 11.4 m in length with a gross tonnage of 12.69, and operates with a single skipper. The Star of David (code/registration C60) is 13.23 m in length with a gross tonnage of 32,and operates with a skipper and single crew. Based on observational monitoring and self-reporting data collected by the Marine Institute in Autumn 2021, these boats suffer depredation rates of 37% and 46% respectively (Burke 2023).

Trials were conducted under license DER-CETACEAN-2022 (Amended 28/04/2023) from NPWS, across normal fishing grounds around the Blasket Islands and larger Dingle Bay area between September 2022 and June 2023, as and when weather conditions allowed (Figure 2). Due to particularly poor weather through October to December of 2022, and February through April of 2023, the majority of work was completed in March and May of 2023, rather than the anticipated Autumn season of 2022.

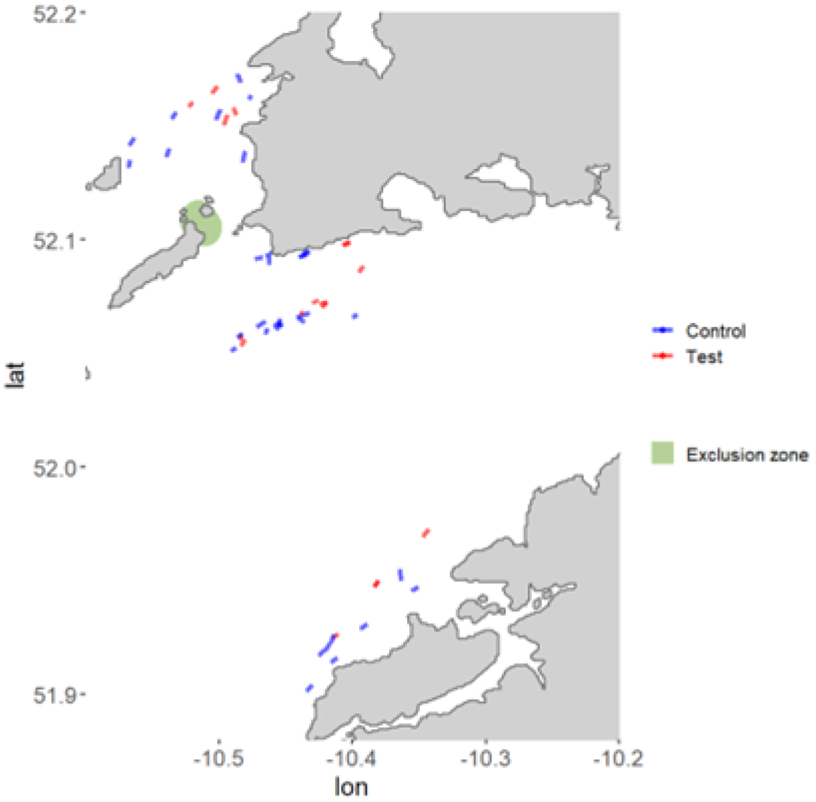

Figure 2. Fishing grounds targeted in the study, with fishing concentrated around the Blasket Islands SAC and Valentia Island where fishers typically operate, and high levels of depredation have been reported. The locations of control and test trials are displayed in blue and red respectively. As per license requirements, no fishing/trials were conducted within a 1 km buffer (highlighted in light green) of the Blasket Islands seal colony haul-out site at White Strand (An Trá Bán).

Trials were run in sets of three net deployments: two control nets and one test net (Figures 3 & 4). All nets were comprised of five sheets of 100 m length each and 5.5 m height (total net length = 500 m long by 5.5 m high). Mesh size of the net was 4 and 7/8's inch knot to knot, and the net was 45 meshes deep. Gauge of the mono was 0.65, and mono-filament colour was light green. Control net deployments followed two configurations (Figure 3). Control net A was deployed with a single SoundTrap (ST600 HF – Ocean Instruments New Zealand Ltd) to record the presence of any cetaceans in the area. The SoundTrap was attached to one end of the net using a system of rope and sub-surface floats to orientate the SoundTrap vertically in the water with the hydrophone pointing downwards 1 m above the top of the net. Control net B was deployed also with a single SoundTrap at one end of the net (as specified above). In addition, one to two sheets of the net were covered in accelerometers at 4 to 8 m intervals along the length of the sheet, positioned centrally vertically (as part of a sister study assessing whole fish removal 'hidden' depredation). Test net C was also deployed with a SoundTrap at one end, and in addition, a second SoundTrap between sheets 2 and 3 or 3 and 4 (to validate the functioning of the TAST device; Figure 3). The SoundTrap was deployed using the same system described for control net A. The TAST was attached to the centre of sheet 3, positioned around 2 m above the net with the transducer facing downwards, and a system of 4 hard buoys hanging 2 m above to keep it in place. On day 6 of the study two SoundTraps were lost (one malfunctioning and the other got detached from the net during deployment and lost at sea). As such, from day 6 onwards, net A had no SoundTrap, and net C had only the central SoundTrap positioned closest to the TAST. SoundTraps were programmed to record continually at a sample rate of 384 kHz. A high pass filter was activated to reduce noise in the 0 to 600 Hz category (potentially from net movement and the boats engine). Pre-amp gain was high (resulting in a maximum sound pressure level (SPL) of around 175 dB re 1 uPa before clipping). The built-in click detector of the device was deactivated, and calibration tones were disabled. The TAST was programmed to operate on a randomised duty frequency of ~1.5-2% (~1.5 prior to January 2023 and ~2 % thereafter) omitted via signals of 200 ms duration. TAST signals transmitted had a frequency centroid of 1.8kHz. The maximum root mean square (RMS) source level in one-third octave bands (TOB) in units of SPL calculated over a 200 ms integration window (corresponding to the signal duration) was ~179 dB re 1µPa. The maximum one-third octave band (TOB) source level in units of sound exposure level (SEL) in was 172 dB re 1µPa^2-s.

One set of trials was run per day of fieldwork (Figure 4). Nets were deployed at one-hour intervals, starting between 8.30 and 9.30 am. The first net deployed (control or test) was not consistent between days. Nets were left in the water for a soak time of approximately 3 hours (the exact soak time was always recorded). Upon net deployment, the location of the start and end of the net, alongside locations of deployed equipment were recorded and sea depth was taken, alongside the time (and time taken to deploy net), and any observations of seals. Prior to all deployments, and in line with license requirements, a 5-minute scan was performed to ensure that there were no cetaceans present within 500 m of the boat. During hauling, the time was recorded (as well as the time taken to haul the net), alongside counts and notes on depredated and undamaged fish (as part of another study assessing TAST efficacy to reduce seal depredation), and any observations of cetaceans and/or seals. In addition to day trials, net B was once singularly deployed overnight as part of a sister trial, and one full set of trials was run overnight to assess the capability of the TAST to operate during overnight soaks. In both instances, net(s) were deployed in the afternoon starting from ~16:00 following the same process as described above.

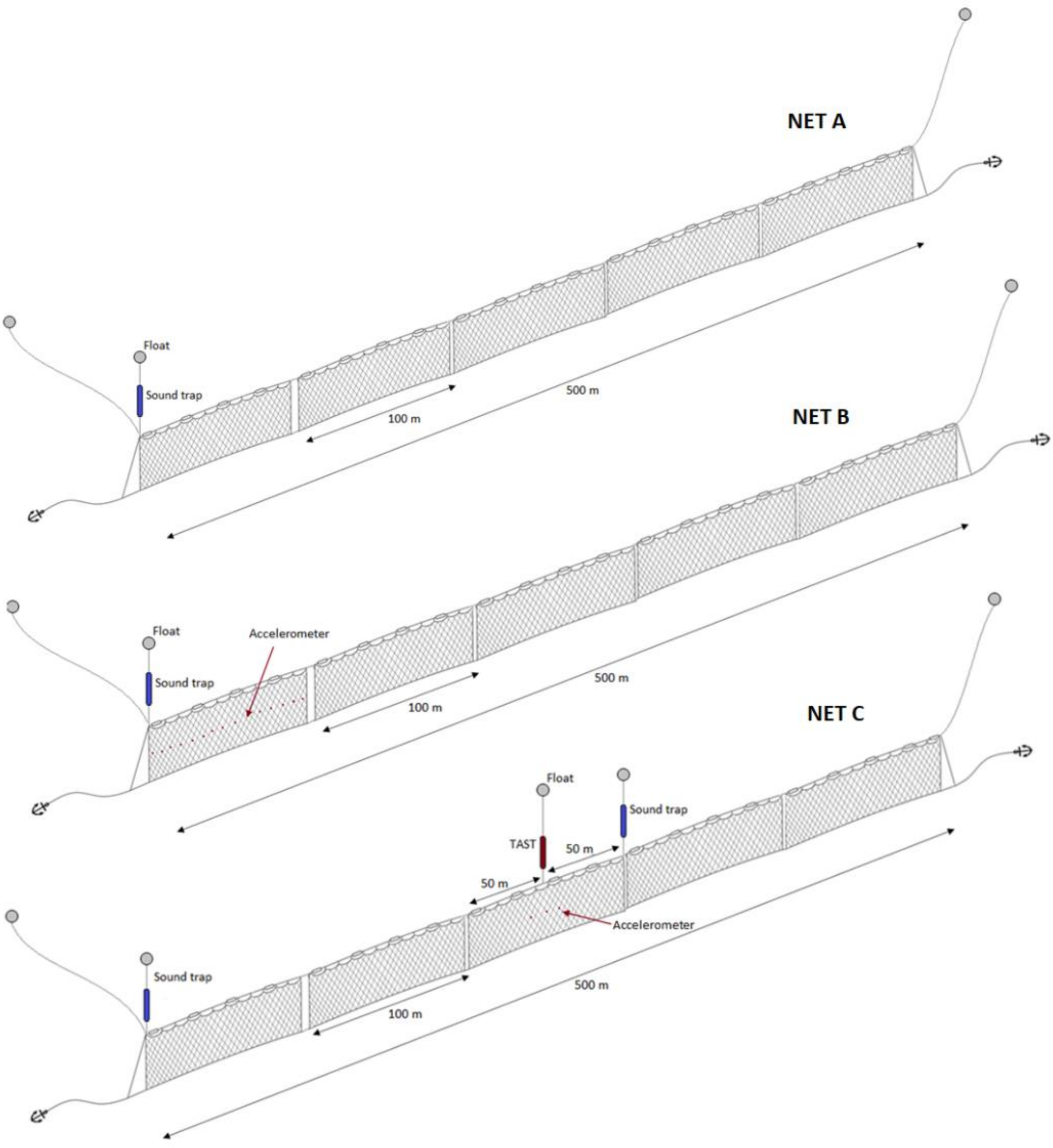

Figure 3. Overview of net set-ups, from top to bottom: (A) control net with SoundTrap, (B) control net with SoundTrap and accelerometers covering one sheet of the net, and (C) test net with TAST, SoundTrap at end of net and a second 50m from TAST, and 3 accelerometers below TAST. Note that on day 6 of the study, two SoundTraps were lost (one malfunctioning and the other got detached from the net during deployment and lost at sea). As such, from day 6 onwards, net A had no SoundTrap, and net C had only the central SoundTrap positioned closest to the TAST.

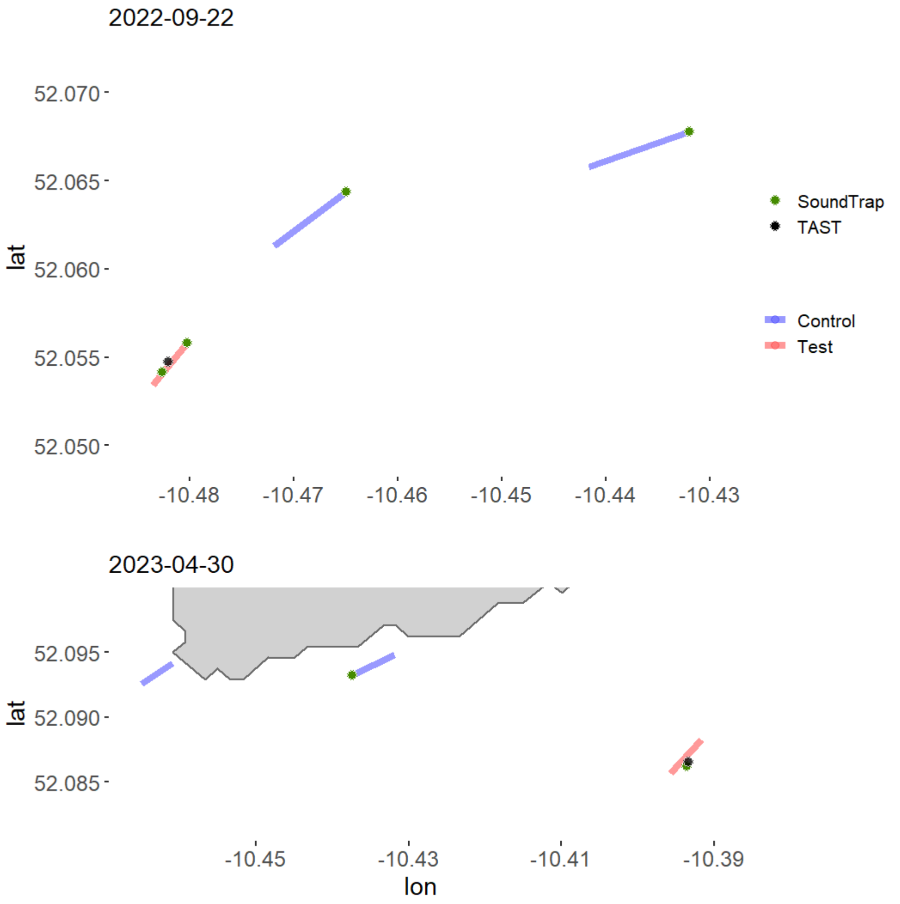

Figure 4. Spatial overview of net/trial set-ups on two dates, before (top) and after (bottom) the loss of two SoundTraps (meaning one control net has no SoundTrap associated with it). Control nets are highlighted in blue, and test nets in red. The location of the TAST is indicated by a black marker, and each deployed SoundTrap by a green marker.

2.2 Data processing

SoundTrap data was processed in PamGuard. For each deployment, SoundTrap recordings were selected from the end of net shooting to the beginning of net hauling. Sound recordings were analysed to detect noises from four sources: (1) sound signals emitted by the TAST, (2) sounds indicative of the presence of whales that may be found in the region (namely minke whales, and fin and humpback whales; Rogan et al. 2018), (3) dolphinid vocalisations from broadband clicks (BB) and whistles, and (4) harbour porpoise narrowband high frequency (NBHF) clicks .

2.2.1 Detection of the TAST

The PAMGuard Whistle & Moan Detector (WMD; Gillespie et al. 2013) was set-up with a narrow bandwidth ranging from 1.7 kHz to 2.2 kHz to detect TAST signals above a signal-to-noise of +8.0 dB in the SoundTrap recordings (full detector specifications provided in Appendix 7.1, Table A1). The WMD works by identifying time-frequency pixels of peak intensity in the Fourier-transformed audio data, and connects neighbouring pixels to identify candidate tonal signals. Following a true signal duration of 200 ms for the TAST, detections with durations less than 150 ms were discarded (this threshold was set lower than 200 ms to accommodate for the detection of weaker signals).

2.2.2 Detection of Fin, Humpback, and Minke Whales

Detection of baleen whale activity was carried out using two different detectors: (1) a binary ResNet18 deep neural network (DNN) to detect minke whale pulse trains, and (2) the PAMGuard Whistle and Moan Detector with a focus on tonal calls from other baleen whales (expected to be humpback and fin whales).

The most documented vocalisation from minke whales in the Northeast Atlantic are pulse trains with a peak frequency between 50 - 150 Hz and duration between 20-60 seconds (Risch et al. 2019). A binary ResNet18 deep neural network (DNN) was employed in Anaconda Navigator (using Python) to recognize minke whale pulse trains from spectrogram representations of the acoustic signal (Muoy et al. 2024). Minimum confidence level was set to 0.1. This detector is still in development but is currently the only detector for minke whale pulse trains for the Northeast Atlantic.

For fin and humpback whales, calls fall between 12-140 Hz, and 100 to 2500 Hz respectively, though humpback song can be as high as 8 kHz. All data were initially down sampled using the decimator module in PAMGuard. The PAMGuard Whistle and Moan detector was then initially set up to detect moans between 0 Hz and 5000 Hz with a signal to noise ratio of 9 dB. As the TAST itself falls within this sound band, an IIR Butterworth Band Stop filter (order 6) was fitted between 1200 and 2200 Hz to filter out the TAST (as without the filter it was routinely picked up by the detector). Manual verification of detections found a very high percentage of false positives, particularly in the 2200 to 5000 Hz band, so to try and reduce the number of false detections, the whistle and moan detector was set up only to detect lower frequency components between 0 Hz and 1200 Hz, thereby excluding the TAST completely. As mid and low frequency moans of humpback whales fall within the 100 Hz to 2500 Hz frequency range, and the TAST covered the upper portion of this range, the decision was made to target only the lower frequencies with this detector, focussing on low and mid frequency humpback and fin whale moans.

2.2.3 Detection of delphinid activity: broadband (BB) clicks, and whistles

The detection of delphinid (dolphin) acoustic activity was divided into two separate workflows.

First, the WMD was set-up to detect narrowband whistles of delphinids between 3 kHz and 30 kHz showing signal-to-noise ratios above +6.5 dB (full detection settings for whistles provided in Appendix 7.1, Table A1). Manual monitoring of the PAMGuard detection process revealed patterns in the varying frequency of false positive detections that motivated post-processing of whistle detections. A high majority of false positive detections were observed to occur overlapping in time with the TAST signal (caused by overtones of the TAST) or were detected in very short duration fragments; fragmentation of detections is a characteristic of the WMD at low signal-to-noise levels (Gillespie et al. 2013). All whistle detections with start or end times during a detection of a TAST signal were discarded from analysis, as were detections less than 50 ms in duration. Some infrequent non-biological tonal sounds with narrow bandwidths were observed to trigger the whistle detector, motivating a final filtering step for whistles where whistle detections that spanned a bandwidth less than 2000 Hz were discarded.

Second, a detector for broadband (BB) delphinid echolocation clicks was set up through the PAMGuard Click Detector module, using the settings provided in Appendix 7.2, Table A2. Our click detector identified candidate click signals in pre-filtered audio data (filter settings provided in Appendix 7.2, Table A2) exhibiting a signal-to-noise ratio higher than 20 dB before subjecting all candidate detections to a spectral classification scheme, which divided detections into three classes: (1) broadband (BB) detections, (2) narrowband high-frequency (NBHF) detections (see section 2.2.2 – detection of harbour porpoise activity: narrowband high frequency clicks), and (3) other detections. Comparison of energy between selected frequency bands and identification of spectral regions of peak frequency were referenced from previous studies (Au & Nachtigall 1997; Robbins et al. 2016) to inform classification of candidate click detections. Delphinid classification compared a test frequency band between 15 and 120 kHz with control bands from 0 to 10 kHz and from 140 to 180 kHz. Clicks showing received levels in the test band that were at least 15 dB higher than those in the control bands on either side were classified as BB clicks. Further details of the settings used for click detection and classification are provided in Appendices 6.2 & 6.3 - Tables A2 & A3. Click detections not spectrally classified as BB or NBHF were discarded.

2.2.4 Detection of harbour porpoise activity: narrowband high frequency (NBHF) clicks

Narrowband high-frequency (NBHF) harbour porpoise clicks were detected with the same PAMGuard click detector used for BB delphinid clicks (see above & Appendix 7.2, Table A2), but were subjected to a different spectral classification scheme (further details in Appendix 7.3, Table A3). Harbour porpoise clicks characteristically show high proportions of energy between 110 kHz and 150 kHz, though this can vary depending on the angle between click's directionality and the receiver (Madsen et al. 2002). To classify NBHF clicks, we compared a test band between 110 and 150 kHz to a lower control band from 0 to 100 kHz and a higher control band from 160 to 180 kHz. Clicks with a received test level at least 20 dB higher than the lower band and at least 5 dB higher than the higher band were classified as NBHF clicks.

2.2.5 Validation of detection performances

All whale detections were manually verified (by Helen Hiley), and detections were determined to be either true positives or false positives. To further validate the results of the detectors, 55.46 hours of recordings across six trials were manually reviewed for baleen whale calls in Adobe Audition 2.0. This was to check for false negatives and help to assess detector performance.

TAST detections, delphinid whistles and clicks, and narrowband clicks were validated by examining 12 hours of randomly selected data (by Tristan Kleyn). This revealed a consistent non-zero background false positive rate for broadband low frequency (dolphin) click detections. These errors, which occurred at an average measured rate of 8.2 false positives per minute across 30 different recording files, were caused by occasional matches of the ambient wave noise around and against the test and control nets with the spectral classification criteria for broadband clicks described above. Ninety percent of manually validated minutes showed a false positive rate less than 18.1 false positives per minute, providing us a per-minute detection threshold above which minutes could be presumed to be true detections with an expected accuracy of 90%. An alternative approach would have been to use a click train detection scheme such as PAMGuard's multi-hypothesis tracking (MHT) click train detector. This detector, however, has been shown to produce false positive rates of up to 20% in backgrounds with varying signal-to-noise ratios (Macaulay, 2020; Webber et al., 2023). Given the high ambient noise levels in our recordings and prioritization of minimizing false positives over minimization of false negatives, we opted for the simpler approach of comparing detection counts to the estimated false positive background, which still allowed for reliable detection of click events. This improvement in detection accuracy found by analysing data in events was extended over whistles, TAST signals, and narrowband clicks, although the average false positive rate per minute for each of these types was found through manual validation to be zero.

2.3 Data analyses

2.3.1 Assessing sound signature and propagation from the TAST

To assess spectral and amplitude characteristics of the TAST sound signals around nets, SoundTrap recordings from test and control nets were analysed. First, we manually selected representative samples from the dataset when the TAST was known to be operating, and calculated one-third octave band (TOB) sound pressure levels (SPL) for standard frequency bins. These values constitute received levels (RL) at the respective distance the measurement was taken. The analysis was conducted using a Fast Fourier Transformation (FFT) method via PamGuide in R (Merchant et al. 2015). The factory-calibrated system sensitivity of each SoundTrap was used as an end-to-end calibration factor yielding TOB band level in units of dB re 1 microPa. We also analysed typical ambient/system noise levels for the selected sections (when no TAST was detected) and present these as an average value.

In a second step we conducted a sound propagation analysis (transmission loss) using recordings from all available SoundTrap deployments for which a distance between the sound trap and TAST had been recorded (via GPS positions). Two-minute samples from each recording when the TAST was known to be operating were filtered with a 10th order Butterworth (LF cut off: 1.4kHz/HF cut off: 2.8kHz) and five representative TAST signals were analysed in Adobe Audition. The filtering was done to remove out of band noise (e.g. from vessel traffic) or animal vocalisations (whistles and clicks) to ensure that (at least by in large) only energy from the TAST signal (and frequency band) was included in the analysis. Consecutively, the relative root mean square (RMS) amplitude was measured and subtracted from the SoundTrap system sensitivity to obtain sound pressure levels in units of dB re 1 Pa (Merchant et al. 2015). These received levels (RLs) constitute broadband SPLs (within the TAST band) which were then plotted against the log (base 10) of distance in metres (Figure 6). In addition, a linear regression model was calculated which contains log10(distance in metres) as a predictor variable and the received levels as the response variable. The model coefficient was used to determine the basic parameter b for transmission loss TL, as TL = b*log10(distance in metres).

2.3.2 Assessing cetacean presence relative to TAST operation

2.3.2.1 Rationale & general considerations

The raw data consists of classified detections of cetacean vocalisation at a given moment in time. Such a dataset represents a textbook case of temporal autocorrelation (i.e. individual data points are not independent of each other but highly correlated in time as vocalisations typically occur in bouts). This poses the risk of pseudo-replication of data (i.e. drawing misleading inferences based on a few influential events) and the risk of violating a key assumption (independence) that underpins most traditional data analysis methods. In turn, this also means that the raw data is not informative in isolation. Simple percentages of cetacean presence, with the TAST being ON/OFF, can be influenced by a few isolated ("one-off”), prolonged events when many cetaceans are present. It was therefore imperative to use an analysis method that fully accounts for these challenges. The data was thus modelled by converting vocalisation counts in five-minute time bins into a binary presence/absence variable based on false positive detection rates (described above). The rationale was that if a vocalisation count is above the false positive detection within a whole five-minute bin there is a reasonable level of confidence that the respective cetaceans were present around the net at that time. In addition, modelling binary data can be beneficial as it mitigates some additional concerns regarding potential violation of model assumptions (e.g. as a result of strong zero-inflation or overdispersion). The mean false positive detection rates per one minute time period was zero for whistles, narrow-band high-frequency (NBHF) clicks and TAST detections but 8.2 for broadband (BB) clicks. The upper 90% confidence interval for BB clicks was 18.1/minute. Hence, we assigned a ‘presence’ state to a five-minute bin if it contained at least 91 BB clicks or one TAST or whistle detection. We deviated on this principle only regarding NBHF clicks where at least two clicks had to be present for a time bin to be considered as NBHF positive. This was done because NBHF echolocation clicks always occur in click trains. While poor signal to noise ratios can mean that some clicks are missed it seems reasonable to expect more than one click to be detected if porpoise were truly present.

As a second and even more important measure, we specified a type 1 auto-regressive correlation structure (AR1) using a grouping factor that specifies continuous timelines in all models. This enables improved reliability of parameter estimates, estimation of more accurate confidence intervals, and better representation of the variance structure by accounting for temporal autocorrelation among observations.

2.3.2.2 Statistical analysis

In addition to the full dataset (Table 1), a more limited subset of the data, which only contained trials for which both control and test nets were deployed at the same time, was analysed separately (referred to as paired trail analysis/data).

We used presence of TAST detection from SoundTrap recordings to code TAST status into two possible predictor variables (candidate variables) which were consecutively assessed during model selection. The first variable assigns TAST ON to any five-minute bin in which at least one TAST signal was detected by the corresponding sound trap on the test net (the closet SoundTrap to the TAST). Any other time bin on any of the nets is considered TAST OFF. The 2nd TAST status variable combines net and TAST status by creating a four-level factor based on detections: TAST detected on test net (high received level), TAST not detected on test net, TAST detected on the control net (very low received level), TAST not detected on the control net. In addition to TAST status, daylight cycle was coded into an additional predictor variable using local times of civil sunrise/sunset.

All data analysis was conducted in R 4.3.1 (R Core Team, 2023). Generalized Linear Mixed Models (GLMMMs) were used to analyse presence of cetacean vocalisations (present/absent) as a function of TAST status (OM/OFF) and diurnal light state (daylight vs nighttime;). Modelling was conducted using the glmmTMB package in R (Brooks et el. 2017). All models were specified with a binomial error distribution and logistic link function. To account for temporal autocorrelation between consecutive time bins we included a term with a first order auto-regressive correlation structure (AR1) in all models. The term was specified as (time-1|tg) in glmmTMB notation where 'time' denotes consecutive time bins and 'tg' (time group) constitutes a grouping factor which specifies continuous timelines (from a single Sountrap deployment). We modelled autocorrelation based on the assumption that autocorrelation is most prominent within a timeline (e.g. one SoundTrap deployed on a given net) with consecutive time bins exhibiting higher auto-correlation than distant ones. In addition to the AR1 term, all models for the paired dataset always included trial ID (1|trial) as a random effect to create a variance structure that allows for direct comparisons between control and test nets (in paired design).

Model selection was conducted using the Akaike Information Criterion (AIC). The rationale behind this was to determine the optimal model while balancing parsimony and explanatory power. The AR1 correlation structure was always part of the model as it was an essential pre-requisite for drawing any inference from the data. The fixed effects (predictor variables) that were considered in the model selection process were the diurnal light cycle (daylight vs night) and either the binary TAST status (binary) or the combined TAST & net status (detected vs not detected). In addition, we considered random effects for SoundTrap ID, trial ID (paired trials only), deployment ID, time group, date (as a factor), and recording ID (nested within SoundTrap ID). Model selection was conducted in a stepwise process (see Zuur et al. 2009). First, the optimal combination of random effects was determined by fitting models with all sensible permutations of random effects and fully populated fixed effects using a restricted maximum likelihood (REML) estimation method. The random effect combination from the model with the lowest AIC was then taken forward into step 2, where the optimal combination of fixed effects was determined (using the previously selected random effects combination). These models were fitted with a maximum likelihood (ML) estimation method. In light of the previously outlined challenges relating to the dataset, the final model was refitted with REML to obtain unbiased estimates of variance components and account for random effects.

In the dataset containing delphinid vocalisations (whistles and BB clicks) the models with lowest AIC typically only contained light status (day vs. night) but not any of the TAST status variables (indicating that TAST status contributed little to the model's explanatory power). However, as it was a primary objective of this study to investigate and estimate any potential effect of TAST we chose to present the models with the 2nd lowest AIC instead. These final selected models all contain binary TAST status (ON/OFF) and light condition (night vs day) as a fixed effect. The more complex TAST status variable that includes net status was not retained in any models (based on AIC). In the whistle dataset the final model included date as a random effect (both for whole dataset and paired trial analyses). The models for BB clicks contained deployment ID and date (all data), and trial and date (paired trials) as random effects.

An initial attempt to apply this approach to the NBHF (harbour porpoise) data was abandoned as widespread convergence failures indicated that the more complex models were overfitting the data. This is likely because NBHF detections were rare throughout the whole dataset meaning that often no contrasts could be estimated across all fixed and random effects. We therefore proceeded with the most simple and sensible model which contained only binary TAST status, an AR1 error structure, and, in the case of the paired trials dataset, trial ID as a random effect to create the corresponding variance structure.

Predicted values and effect size estimates with associated 95% confidence intervals were obtained using model contrasts (least square means) in the emmans package (Lenth 2024). All model coefficients (β) and associated confidence intervals (Cis) were back-transformed and are presented on the scale of the response variable (e^{β}). This means that effect size measures (e^{β}) constitute odds ratios i.e. they represent a chance in the odds of detecting cetacean vocalisations (encountering a vocalisation positive 5min time bin) as a function of the predictor variables (fixed effects). Predicted values were also obtained from emmeans, and constitute mean predictions on the population level of the random effects while taking random effects variance into account. Confidence intervals (CIs) either show the range within which 95% of future observation data will likely occur (predicted values), or the interval within which the model coefficient/effect size estimate (e^{β}) will occur with a 95% likelihood (effect size/odds ratios). The estimated p-values represent the likelihood of the effect size estimate being different from chance.

Auto-correlation between consecutive time bins was assessed by inspecting autocorrelation function (ACF) plots of the Pearson residuals (using the index number of data points). This showed clearly that the AR1 structure greatly improved the auto-correlation problem and successfully accounted for auto-corelation in most models, even though some lags still marginally exceeded the expected confidence interval. Further diagnostics were carried out by assessing scaled residuals using the DHARMa package (Hartig 2022). However, one should note that the interpretation of these can be problematic in binomial models. There was some evidence for heterogeneity of variance across the factor levels of the predictors, but this was deemed acceptable.

3. RESULTS

A total of 19 days of data collection were completed between September 2022 and June 2023 (Table 1). The trial was paused one day short of the 20 anticipated days due to a combination of equipment malfunction (and delays in servicing) alongside consistently poor fishing conditions and a shortage of workable weather windows. On 17 out of 19 days, 17 grouped control-test trials were successfully completed. On the other two days, due to TAST failure, only control net deployments were completed.

One additional grouped overnight soak was completed, although the battery of the TAST ceased ~ 6 hours into this trial. Another single net (net B) was set for an additional overnight soak as part of a sister study, yielding additional information on cetacean activity in the absence of the TAST.

Across the 17 days of grouped day trials, nets were deployed for an average soak time of 2.9 hrs (range = 1.9 to 3.65 hrs; Table 1). An additional 92.1 hrs of SoundTrap recordings were obtained across an additional eight deployments, including four overnight soaks averaging 17.5 hrs (range = 16.1 to 20.4 hrs; Table 1), resulting in 53.7 hrs of the 92.1 hrs of recordings occurring during the night. The dataset used in statistical analyses of cetacean vocalisations contained 2531 five-minute time periods totalling around 211 hours of effort. Analysis of the paired trial only data contained 1836 five-minute time periods yielding 153 hours of acoustic observations (including one set of overnight soaks).

Table 1. Trial dates with configuration of net's deployed, number of SoundTraps deployed on each net, trial start time (end of shooting of first net in water), trial end time (start of hauling of last net out of water), and submerged soak times. '–' represents where a net was not deployed. On the 1st and 2nd March 2023, data was unavailable from the SoundTrap deployed on net C as the SoundTrap was lost at sea on the 2nd March 2023 (so SoundTrap number is noted as 0 on these nets).

Trial date	**Nets deployed**			**SoundTraps**			**Trial start time**	**Trial end time**	**Soak time (hrs)**		
	A	B	C	A	B	C			A	B	C
22-09-2022^{+}	Y	Y	Y	1	1	2	09:12	13:07	1.9	2.0	2.3
22-09-2022	-	Y	-	-	1	-	14:44	11:09*	-	20.4	-
23-09-2022^{+}	Y	Y	Y	1	1	2	10:06	15:51	3.6	3.2	3.2
23-09-2022^{+}	Y	Y	Y	1	1	2	16:31	10:45*	16.1	16.6	16.7
24-09-2022	-	Y	-	-	1	-	12:47	15:39	-	2.9	-
03-12-2022^{+}	Y	Y	Y	1	1	2	09:06	13:38	3.0	2.7	2.4
01-03-2023^{+}	Y	Y	Y	1	1	0	09:26	13:25	2.9	2.5	2.0
02-03-2023^{+}	Y	Y	Y	1	1	0	09:05	13:35	2.5	2.8	3.0
03-03-2023^{+}	Y	Y	Y	0	1	1	09:19	14:11	2.9	2.9	2.8
04-03-2023^{+}	Y	Y	Y	0	1	1	09:32	14:42	3.0	3.2	3.1
05-03-2023^{+}	Y	Y	Y	0	1	1	08:48	14:16	2.9	3.0	3.5
06-03-2023^{+}	Y	Y	Y	0	1	1	08:32	13:28	2.9	3.0	2.9
27-04-2023^{+}	Y	Y	Y	0	1	1	09:33	14:52	3.3	3.4	3.2
28-04-2023^{+}	Y	Y	Y	0	1	1	09:30	14:45	3.2	3.2	3.1
29-04-2023^{+}	Y	Y	Y	0	1	1	09:05	14:17	2.9	3.1	3.1
30-04-2023^{+}	Y	Y	Y	0	1	1	08:38	14:13	3.6	3.4	3.3
01-05-2023^{+}	Y	Y	Y	0	1	1	09:25	14:22	2.9	3.0	2.9
02-05-2023^{+}	Y	Y	Y	0	1	1	09:25	14:30	3.0	3.2	3.0
12-05-2023^{+}	Y	Y	Y	0	1	1	08:38	14:16	3.3	3.4	3.7
13-05-2023^{+}	Y	Y	Y	0	1	1	08:42	13:24	2.8	2.7	2.8
15-05-2023	Y	Y	-	0	1	-	09:01	12:55	2.9	2.9	-

**Indicates where the hauling time was a following day.*

$^{+}$Indicates trial days used for paired trial analyses

3.1 Sounds propagation & acoustic characteristic of the TAST

The acoustic characteristics of the TAST signal around the test and control nets in units of one-third octave band (TOB) sound pressure levels (SPL) at different distances is shown in Figure 5. The example from the test net (~180 m distance; red line) shows the highest TOB received levels (~137dB re 1Pa) in a frequency band centred at ~1.6 kHz. In some cases, received levels already dropped below ambient noise at 1.2 km distance (green line), while in other cases the signals could still be detected at a similar distance (cyan line). Ambient noise levels (in TOBs) were typically around 90 dB in the shown examples at frequencies between 1kHz and 10kHz.

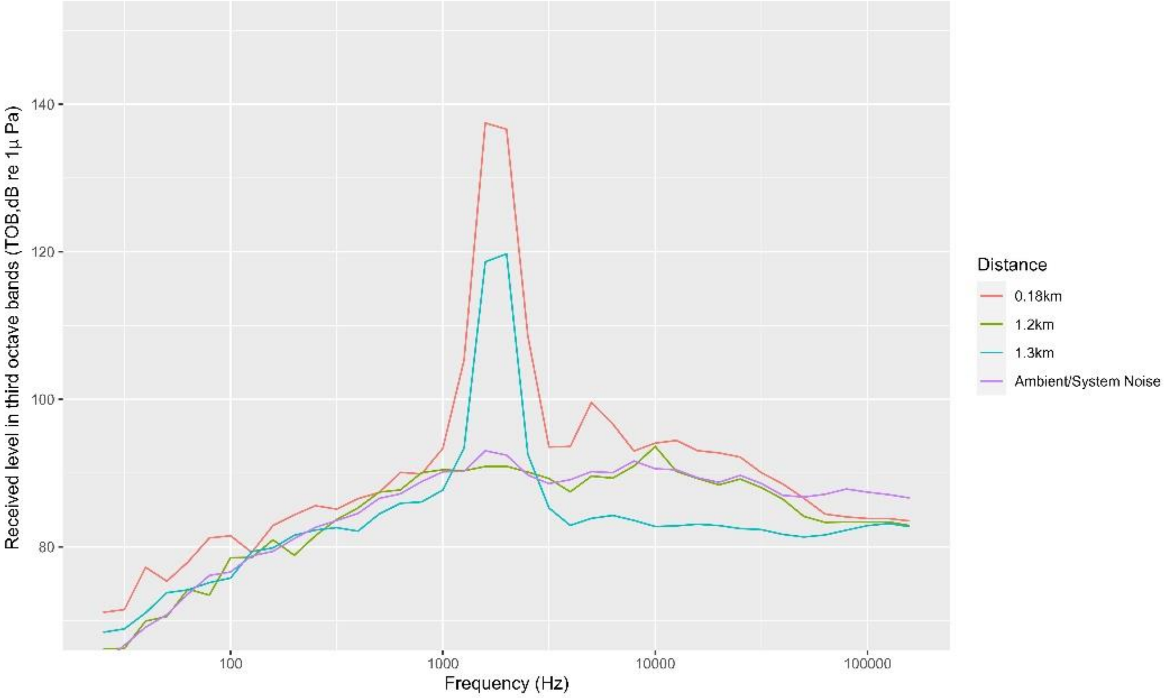

Figure 5. Ambient noise levels (purple line) and acoustic characteristics of the TAST signal measured on test and control nets at differing distances (red, green, and cyan line). The graph shows one-third octave band (TOB) received levels (sound pressure levels in dB re 1 µPa) for respective frequency bands. The red line constitutes a recording on the test net (180 m distance). The green line shows a recording in which the TAST signal dropped below ambient noise at 1.2km distance (not detected), while the turquoise line provides an example where the signal is still ~25dB above ambient noise at a similar distance.

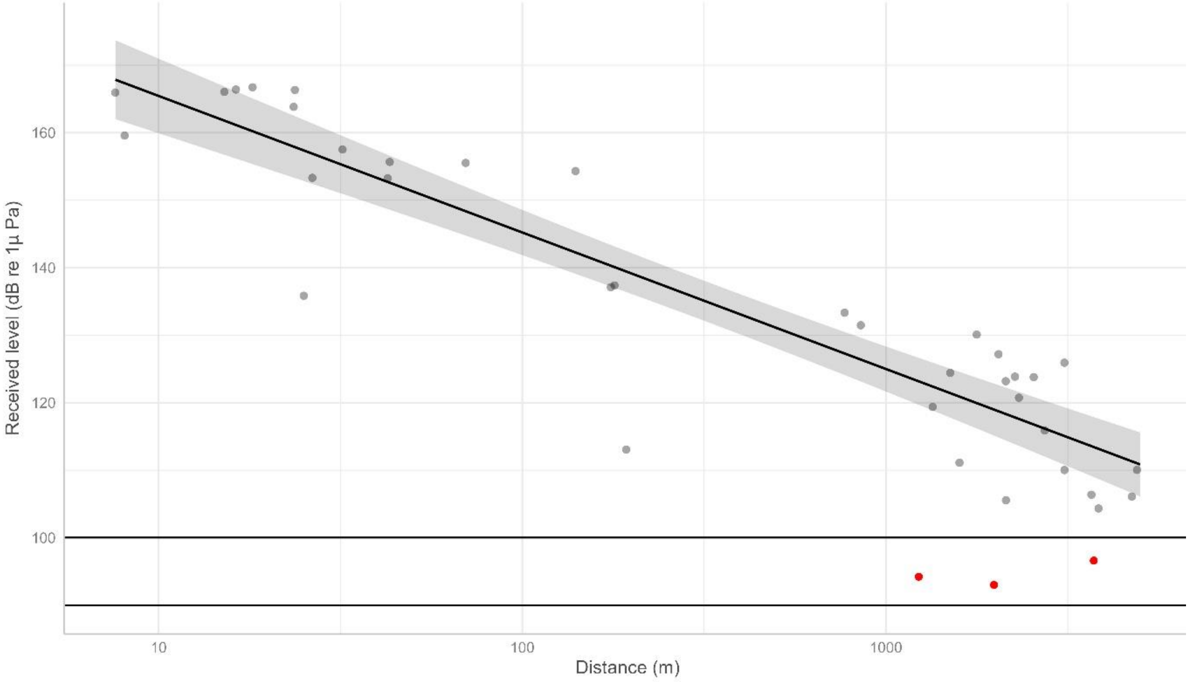

*Figure 6. Sound propagation of TAST signals around static gillnets as broadband (in-band) received levels as a function of distance in metres (on log10 scale). The solid line and the shaded area represent the predicted values from a linear regression model and associated 95% confidence interval. The model coefficient indicates 20.2 *log10 transmission loss as a function of distance (in metres). The red dots represent the ambient noise (in the same band) in cases when the TAST signal could not be detected in the recording. The solid lines show a typical range of in band ambient/system noise levels.*

Figure 6 shows broadband received levels (SPL in dB re 1) plotted against the logarithm (base of 10) of distance. The linear regression model for the sound propagation shows that there was a highly significant effect of distance (F = 176, df = 34, $p < 0.001$) on received sound levels. The model explains 83% of variance in received levels (adjusted R squared = 0.83). The model coefficient (**β**) indicates transmission loss of 20.2*log10 as a function of distance in metres. Transmission loss is therefore slightly higher than expected by spherical spreading losses (20*log10(distance)) and significantly higher than cylindrical spreading losses (10*log(10(distance))). This shows that received levels are dropping quickly as a function of distance in line with highest known mode of transmission loss in the marine environment. At distances of more than 1km there were several occasions when TAST signals could not be detected anymore, i.e. the signal level dropped below ambient noise levels (red dots in Figure 6). Again, ambient noise levels typically ranged from 90dB to 100dB in the frequency band of TAST.

3.2 Cetacean presence relative to TAST operation

<u>3.2.1 Detection of baleen whale</u>

Across the study period, the minke detector made 70 detections and the WMD made 1606 detections, all of which were false positives (i.e. no minke, humpback or fin whales were detected). Boat noise was the primary reason for false positives from both detectors. Other false detections included (but were not limited to) fish grunts and possible seal calls. However, 10 minke whale pulse trains were detected through manual auditing of a subset of the trial data (55.46 hours) (Figure 6). These all occurred within 1h during a single event, when the TAST was not present in the water.

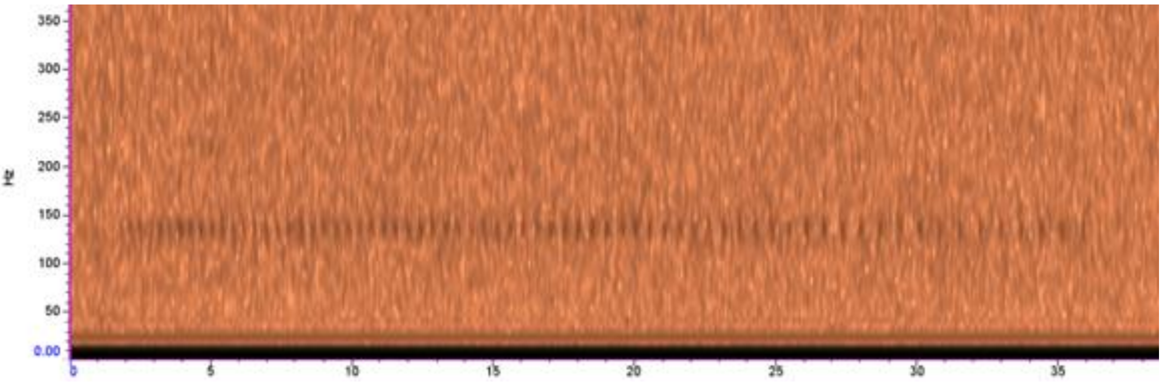

Figure 6. One of 10 Minke Whale pulse trains detected during trials.

3.2.2 Detections of delphinids

3.2.2.1 Delphinid whistles

The final models for both datasets (all and paired trials) included the binary TAST status (ON/OFF) and diurnal light state as predictor variable. The more complex predictor of TAST detection by net type (control/test) was not retained in the model selection process.

Delphinid whistles were detected regularly throughout the whole experimental period. The predicted values from the model show the probability of detecting delphinid whistles as a function of diurnal cycle (night/day, Figure 7) and TAST state (ON/OFF, Figure 7). There was no significant difference in the probability of detecting whistles on the test net when the TAST was ON compared to when it was OFF across either dataset (all trials: p=0.92, paired trials: 0.94, Table 2). The effect size estimates (odds ratio) are both close to one (all trials: $\mathbf{e}^{\beta}$**=** 1.06, paired trials: $\mathbf{e}^{\beta}$=1.07) confirming that the TAST did not exert an effect on the likelihood of detecting dolphin whistles around the net (see also Table 2). In contrast, diurnal state (night/day) exerted a strong effect on whistle detection probabilities (Figure 7). This effect only constituted a trend (p = 0.07) for the overall dataset which indicated a ~4 times higher likelihood of detecting whistles in the day ($\mathbf{e}^{\beta}$ = 4) compared to night. However, the effect of diurnal state was highly significant (p = 0.004) in the paired trials (see also Table 2). The effect size estimate predicts that the odds of detecting dolphin whistles ($\mathbf{e}^{\beta}$) is ~11 times higher (CI: 2/56) during night compared to daylight hours (Table 2).

The predicted values from the model for the whole dataset show the estimated detection probability for dolphin whistles (Figure 7). When expressed as percentages, whistles are predicted to be encountered 26.6% of the time at night when the TAST is OFF and 27.8% when the TAST is ON. The estimates are around 7.9% (OFF) and 8.4% (ON) for daylight hours (Figure 7). In the paired dataset, the estimated detection likelihoods are 8.3% (TAST OFF) and 8.6% (TAST ON) during the day but 50.9% (ON) and 49.8% (OFF) during the night. The confidence intervals around these estimates are large, indicating variability within predictor and random effect variables.

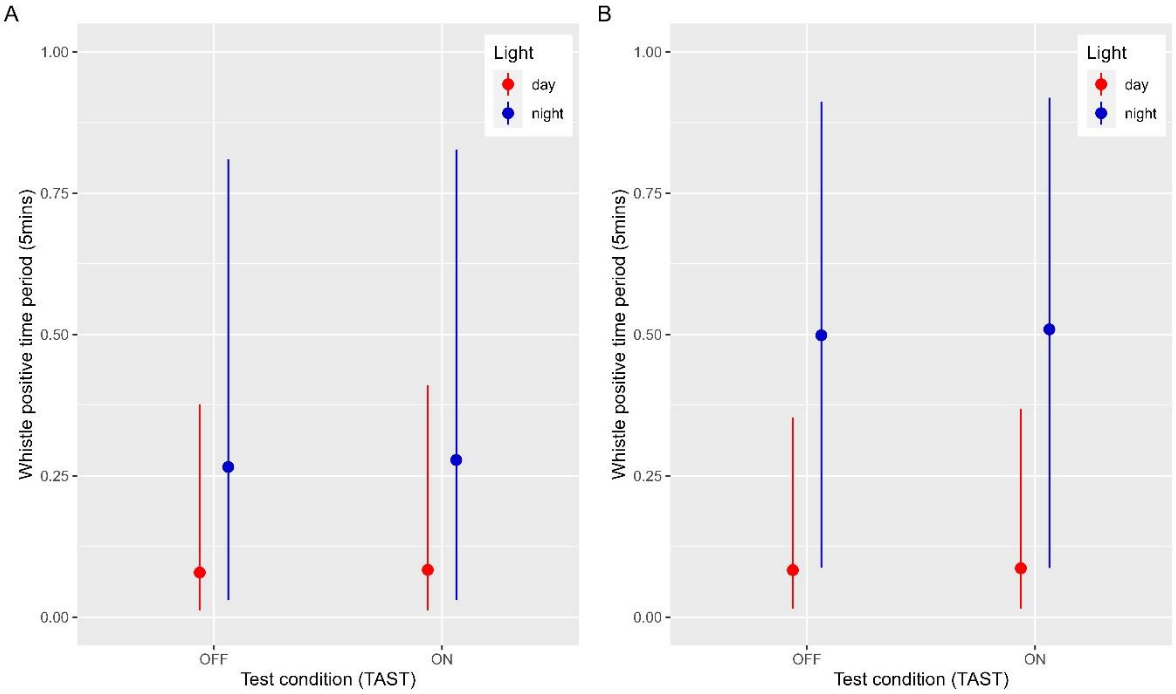

Figure 7. Probability and 95% confidence intervals (CI) of whistle presence within a five-minute time bin when the TAST is ON/OFF during daylight (red) and night (blue) hours for complete dataset (A), and paired trials only (B). Detection probabilities and CIs constitute mean model predictions on the population level average of the random effects (obtained from emmeans). The difference between day and night hours is significant at p=0.004 for the paired trails (B) only (see also Table 2).

Table 3. Effect sizes (odds ratios), 95% confidence intervals and p-values for the fixed effects of light & TAST status from the models for both datasets analysing delphinid whistles.

EFFECT	**ODDS RATIO e^{β}**	**LOWER CI**	**UPPER CI**	**p-VALUE**
Complete dataset				
Night / Day	4.220	0.859	20.735	0.076
ON / OFF	1.065	0.314	3.611	0.920
Paired trials only				
Night / Day	10.956	2.131	56.328	0.004
ON / OFF	1.043	0.349	3.113	0.940

3.2.2.2 Delphinid clicks (broadband BB clicks)

The selected models for both datasets (all and paired trials) included binary TAST status (ON/OFF) and diurnal state as predictor variables. The more complex predictor of TAST detection by net type (control/test) was not retained in the model selection process.

The predicted values from the model show the probability of detecting delphinid clicks as a function of day/night (Figure 8) and TAST state (ON/OFF, Figure 8). Figure 8 shows that broadband (BB) clicks were detected frequently throughout the whole experimental period. There was no significant difference in the probability of detecting clicks on the test net when the TAST was ON compared to when it was OFF (all trials: p = 0.97, paired trials: p = 0.90, Table 3). The effect size estimates (odds ratio) are both very close to one (all trials: $\mathbf{e}^{\beta}$= 0.98, CI: 0.30/3.1, paired trials: $\mathbf{e}^{\beta}$=0.93, CI: 0.31/2.8) demonstrating the TAST did not have any effect on the likelihood of detecting dolphin clicks around the net (see also Table 3). Unlike TAST status, diurnal state (night/day) exerted a strong effect on click detection probabilities (Figure 8). This effect was significant in both the overall dataset (p = 0.01) and paired trials (p = 0.019). The odds ratio for the overall dataset indicates a ~9 times higher likelihood of detecting clicks at night compared to during the day ($\mathbf{e}^{\beta}$ = 9). The effect size estimate for the paired trial dataset predicts that the odds of detecting dolphin clicks is ~11.8 times higher ($\mathbf{e}^{\beta}$ = 11.8, CI: 1.5/92.8) during night compared to daylight hours (Table 3).

When expressed as percentages, clicks are predicted to occur in ~25% of all time bins during the night but only ~3.5% during the day (Figure 8, ON = 3.4%/OFF = 3.5%) across the complete dataset. In the paired dataset the estimated likelihoods for encountering delphinid clicks are 5.3% (TAST OFF) and 4.9% (TAST ON) during the day and 37.8% (ON) and 39.5% (OFF) during the night. The confidence intervals for these estimates are large indicating variability within predictor and/or the contextual random effect variables (i.e. date, trial ID (paired data) and deployment ID (complete data)).

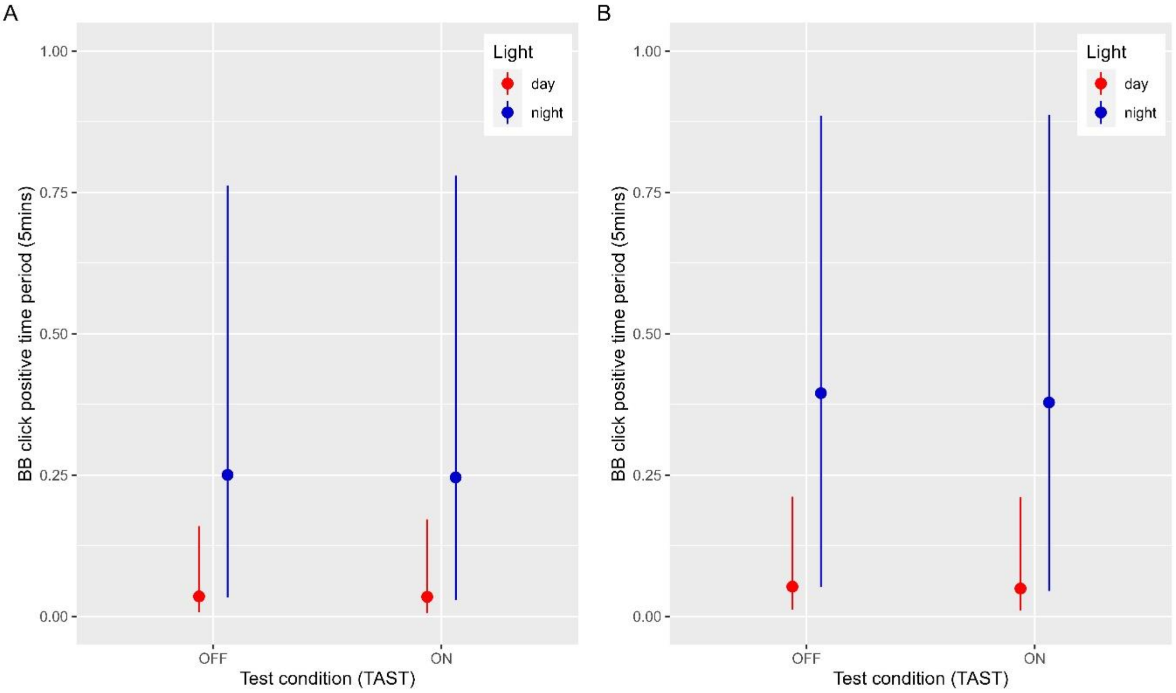

Figure 8. Probability and 95% confidence interval (CI) of presence of broadband (BB) clicks within a 5min period when TAST is ON/OFF during daylight (red) and night (blue) hours for the overall dataset (A) and paired trial only (B). Detection probabilities and CIs constitute model predictions on the population level average of the random effects (obtained from emmeans). The difference between day and night hours is significant at p=0.0 for the paired trails only.

Table 3. Effect sizes (odds ratios), 95% confidence intervals and p-values for the fixed effects of light & TAST status from the models for both datasets analysing delphinid clicks.

EFFECT	ODDS RATIO e^{β}	LOWER CI	UPPER CI	p-VALUE
Complete dataset				
Night / Day	9.123	1.689	49.271	**0.010**
ON / OFF	0.977	0.304	3.136	0.968
Paired trials only				
Night / Day	11.751	1.487	92.829	**0.019**
ON / OFF	0.933	0.312	2.790	0.901

3.2.3 Harbour porpoise activity (narrow-band high frequency; NBHF)

Detections of NBHF clicks were extremely rare throughout the whole dataset irrespective of TAST status or diurnal state (Figure 9). This made any statistical inference challenging and means results should be interpreted with caution (see discussion).

The models for both datasets suggest that there was no significant difference in NBHF click detections when the TAST was ON compared to when it was OFF (all data: p=0.3, paired trials: p= 0.28). While coefficients are below one, confidence intervals for the effect size measures are huge and range from a negative to positive effect (Table 3). Predicted detection rates for NBHF clicks from the model range from 0.15% to 0.8% with confidence intervals extending up to 2.6% (Figure 9).

As all of this indicates that the model with TAST status as the only predictor variable captured little of the variability in NBHF click detections, so we also investigated additional predictor variables, namely potential interactions between species groups. In the overall dataset, the percentage of time bins which contained NBHF clicks was lower when BB clicks were present (1%) compared to when no delphinid clicks were detected (2.2%). When using a combined ‘dolphin presence’ variable (BB clicks or whistles present), this difference in the paired trial data gets more prominent (i.e. porpoise were only detected in 0.3% of time bins when dolphins were present compared to 1% when no dolphins were present). As this is based on the raw data it is hard to say whether these trends are real, however, the number of porpoise detections was insufficient to include additional variables in a more complex model.

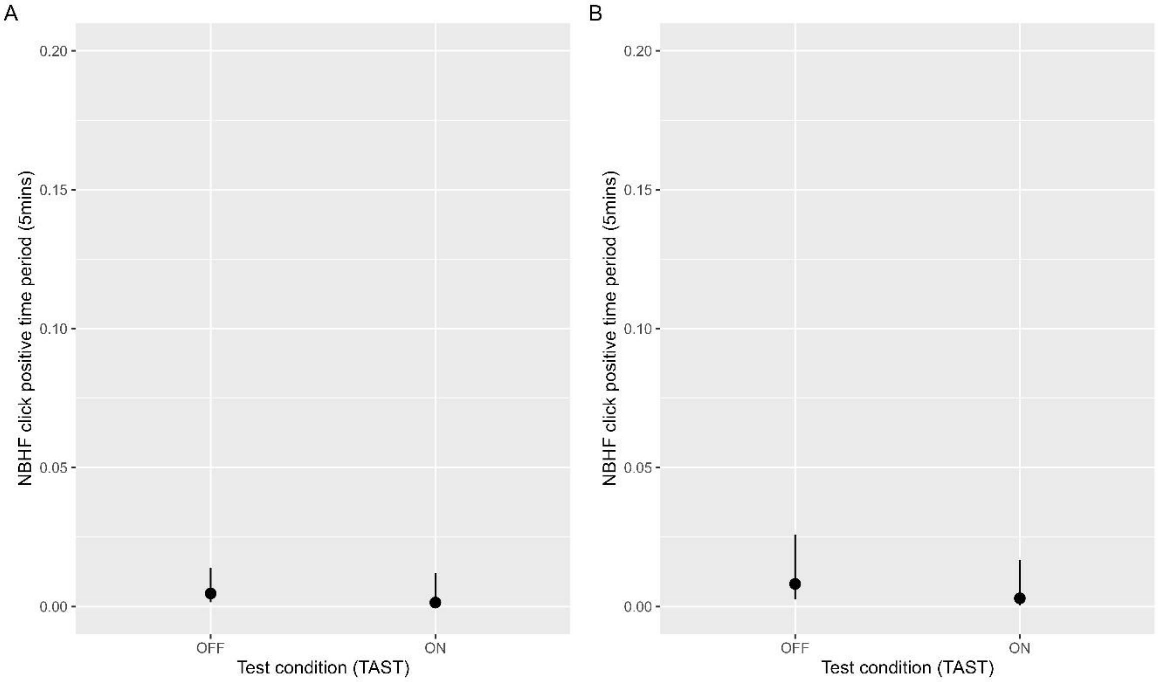

Figure 9. Probabilities and 95% confidence intervals (CI) of presence of narrowband high-frequency (NBHF) clicks within a five-minute time bin when the TAST is ON/OFF for the overall dataset (A) and paired trials only (B). Detection probabilities and CIs constitute mean model predictions on the population level average of the random effects (obtained from emmeans). The are no statistically significant differences in presence when the TAST is ON or OFF. Please note the differing scale on the y-axis compared to delphinid data.

Table 4. Effect size (odds ratio), 95% confidence interval and p-values for the fixed effect of TAST state from models for both datasets analysing NBHF (harbour porpoise) clicks.

EFFECT	ODDS RATIO e^{β}	LOWER CI	UPPER CI	p-VALUE
Complete dataset				
ON / OFF	0.364	0.051	2.589	0.313
Paired trials only				
ON / OFF	0.310	0.037	2.604	0.281

4. DISCUSSION

We collected over 200 hours of acoustic recordings during 19 trials days and an additional two nights of overnight deployments, across 40 and 18 control and test net deployments respectively. These recordings were examined for TAST signal presence and cetacean vocalisations. TAST sound signals were in line with factory calibration and dropped quickly with distance from the TAST, indicating a highly localised deterrence effect that does not propagate over large distances. Vocalisations of baleen whales were rare, with only a handful of encounters identified. Delphinid vocalisations were encountered frequently during the study. Statistical analyses of these vocalisations demonstrated near identical detection likelihoods for delphinids when the TAST was ON and OFF, with models providing evidence for no effect being exerted by the TAST (odd ratio close to one). Harbour porpoise detections were rare overall, and while we found no evidence of differences in porpoise presence with TAST operation/presence, no definitive conclusions can be drawn.

4.1 Sound propagation and noise footprint of the TAST

Acoustic analyses show that the TAST signals sound characteristics recorded on the nets are in line with factory calibrations. The TOBs with the most energy are centred at ~1.6khz or 2khz, with little spillage towards higher frequency bins. Received levels (RL) dropped off quickly with increasing distance and a transmission loss of 20.2 *log10 of distance (in metres) was found around the static set nets. This is marginally higher than expected from cylindrical spreading losses of at 20*log of distance. Previous studies using earlier prototypes of the TAST, emitting sound signals centred at 1kHz, found values ~18*log10 of distance (e.g. Götz & Janik 2015). This difference is not huge (given the variability) and highlights the fact that geometrical losses signals from the TAST typically propagate reasonably close to spherical spreading, the highest mode of transmission loss. While the TAST signals have sufficiently high received levels to cause a localised deterrence effect in the target-species (e.g. Götz & Janik 2015, 2016), signals quickly drop below the startle threshold of the respective species and therefore do not affect animals over large ranges (e.g. Götz & Janik 2015). When assessing effects on non-target species, one must consider their hearing sensitivity in respective frequency bands in addition to the TOB level of sound within that frequency band. Delphinids (and phocoenids) have less sensitive hearing at lower frequencies of 1.8 kHz (see Southall et al. 2019) which in conjunction with the high measured transmission losses explains the frequent presence of clicks and whistles around the nets. Baleen whales do have good low frequency hearing but their absolute hearing thresholds are higher than the thresholds of porpoise at high frequencies (Southall et al. 2019). While the TAST sound signal could on some occasions be detected over a range > 1 km, the signal to noise ratio was low and the signal would not be capable of eliciting a startle response and adversely effecting animals (target or non-target species; see Götz & Janik, 2015). Due to its short duration and pattern of emitting isolated signals with large signal intervals at overall low duty cycles (1.5-2%), masking potential is also low.

4.2 Whale detections

Minke whales have been found to be most vocally active between August and November in the Northwest Atlantic (Risch et al 2013), and between June and November in the North Sea (Risch et al 2019). A clear diel pattern in pulse train occurrence has also been shown, with most detections occurring during night (Risch et al 2013, Risch et al 2019). Of the 17 trials appropriate for test-control comparisons, only three took place during the seasonal period when minke whales are expected to be most vocally active, but none of these encompassed night-time recordings. Two additional trials (one single control net deployment and one grouped when the battery of the TAST failed) that occurred during September (appropriate season) and at night were manually reviewed to ensure the detector had not missed any detections. 10 pulse trains were detected in those files, all of which took place on the 23/09/22 between 04:30 and 05:30, when no TAST device had been deployed. An additional four trials were manually reviewed, and no further minke pulse trains were identified.

No fin whales or humpback whales were detected either with the WMD, or when manual reviewing files. The WMD performed very poorly, so manual reviewing of the data provides the best estimate for true detections here. Seasonality of fin and humpback whale vocal behaviour has also been shown in the Northeast Atlantic, with humpback detection occurring primarily during March and April in Irish and Scottish waters, and fin detections peaking in October through to January (Berrow et al 2018, van Geel et al 2023). Only one trial took place during the peak period for fin detections which may be a reason for limited detections here. Of the remaining trials, nine took place during March and April. Two trials were manually reviewed during this period with no whale detections found (both early April). Humpback detections were found between late March and April in the Observe project (Berrow et al 2018), so the March trials, which took place between 1st and 6th March, may be too early for humpback detections to occur in this region.

4.3 Delphinid detections

Delphinid vocalisations were detected frequently throughout the experimental period with predicted detection rates as high as 51% at night and 8% during the day (whistles). The highest estimates for clicks were 40% during the night and 5% during the day. No statistically significant difference in detection probabilities was found between times when the TAST was ON or OFF and detection probability estimates are identical for both treatment levels. This is supported by the fact that effect size estimates/odds ratios are close to one, therefore providing further evidence for no change in the presence of delphinid vocalisations around the nets as a consequence of TAST operation. Given higher received levels of signals from the TAST around the test net did not cause any change in delphinid presence (when the TAST was ON), it is even less likely that delphinids would be impacted at further distances (e.g. in cases when the TAST was detected at much lower received levels around control nets). This is supported by the fact that the four-level factor for TAST status (test net: ON/OFF, control: detected/not detected) was not retained during model selection indicating that it generally had low explanatory power. In addition, it may be worth noting that the highest quality model lowest AIC did not even include binary TAST status (but only daylight status), indicating that TAST status had little explanatory power (i.e. it contributed little to goodness of fit).

The sustained presence of delphinid vocalisations around the test net when the TAST was ON compared to the control net and OFF periods on the test net can be interpreted as a proxy for sustained and unaffected presence of delphinids around the test net. The most parsimonious interpretation would probably be that the TAST did neither deter nor attract dolphins. However, it is important to bear in mind that we did not directly measure presence or movement behaviour of cetacean, but presence of vocalisations. These are in turn the result of behavioural state and environmental factors. While we couldn't quantify behavioural states from the SoundTrap data, the analysis provides strong evidence for an effect of diurnal light cycle on the detection probability of delphinids. The models for both whistles and BB clicks indicate 4 to ~12 times higher detection probabilities of vocalisations during the hours of darkness compared to daylight hours. This could either be the result of an increased presence of delphinids around the nets during nighttime, or perhaps more likely, an effect of higher nighttime vocalisation rates. Higher nighttime vocalisation rates makes sense as visual cues are rare during the night and increased echolocation use would be beneficial for navigation and prey capture while increased whistle use may be necessary to maintain group cohesion at night. This has been well documented in comparable studies for various cetacean species, particularly regarding echolocation clicks. An increase in nocturnal echolocation detections of cetaceans has now been exhibited in many PAM studies for dolphins (e.g. Cárdenas Hinojosa et al. 2019, Cascao et al. 2020) and for harbour porpoises (e.g. Carlstrom, 2005, Williamson et al., 2007, Todd et al 2009). Pacific white sided dolphins have been found to alternate between two different click bout patterns from day and night (Soldevilla et al., 2010b), and Risso's dolphins (Soldevilla et al., 2010a) and melon headed whales (Baumann-Pickering et al., 2015) have also been found to increase click rate during the hours of darkness. In Scotland, bottlenose dolphin detection rates were higher during the day in the spring and summer, but higher at night in Autumn and winter (Fernandez-Betelu et al., 2019). The increase in nocturnal detections for porpoises has recently been attributed to changes in behavioural state and detectability (Macaulay et al., 2023), rather than changes in abundance or site usage, and it likely that this is the case with dolphins here.

Analyses of BB clicks and whistles show broadly similar patterns. Whistle detections were more frequent than click detections, but confidence intervals are large. This difference may be the result of the fact detection ranges for whistles are typically larger than for clicks, which may in part be due to high absorption losses at higher frequencies but also the higher directionality of clicks compared to whistles. Echolocation clicks are emitted in a very narrow beam, and detection by the SoundTrap will require a dolphin to direct its echolocation beam towards the net (on-axis) or be close to the net so as off-axis clicks can be detected as well. In contrast, whistles have a broader transmission beam meaning that detection likelihoods will be higher, even at off-axis angles (when dolphins are not facing the SoundTrap). Differences between day and nighttime hours were much stronger for clicks than for whistles. This is in line with previous studies, that have found that whilst echolocation increases in darkness, socials signals will increase during the day (Cascao et al. 2020). This may in turn be a result of the fact that echolocation clicks use may be more strongly driven by light state than whistles are. Whistles are important for maintaining medium-range group cohesion and coordination (Quick & Janik 2008, Quick & Janik 2012, King et al. 2016), but this is also relevant during the day when individuals are out of sight. On the other hand, short-range echolocation will be essential for successful nighttime navigation, obstacle avoidance and foraging behaviour but may be less relevant during the day.

4.4 Harbour porpoise activity

In contrast to delphinid vocalisation, detection of NBHF clicks was rare and the highest estimates for detection rates were only ~1%. Porpoise detection positive time bins were rare and often contained only a few clicks. Model coefficients for the TAST effect were below one but there is no statistically significant difference in detection probability across TAST states and confidence intervals are huge. On balance, the most parsimonious explanation is that there was no effect of the TAST (short or long-range) on porpoise presence. This would be in line with previous studies using TAST signals in a similar frequency range (1kHz), which showed no effect on abundance and behaviour of visually tracked harbour porpoise around fish farms (Götz & Janik 2015, 2016). This stands in contrast to conventional mid to high-frequency and high-power ADDs/AHD which can cause large-scale habitat exclusion in porpoise (Johnson 2002). While no effect may be the most likely interpretation, infrequent detection events which prevent more complex models from being fitted make it difficult to draw any definitive conclusions. While we cannot entirely exclude the possibility of a small and highly variable effect of the TAST at close proximity, large confidence intervals mean that no clear conclusions can be drawn. More data with more frequent porpoise detections would be needed to investigate this in more detail.

Low harbour porpoise detections here may reflect substantial decreases in harbour porpoise abundance in the region over the last few years (O'Brien and Berrow, 2018). An alternative explanation for the overall low detection rates for porpoise in our study may be found in inter-species interactions. In the raw data, the percentage porpoise-positive time bins were much lower (0.3%) when dolphin vocalisations were detected at the same time compared to time periods when dolphins were absent (1%). While we cannot distinguish dolphin species in the acoustic monitoring data, the two most likely candidates in the area are bottlenose dolphins (*Tursiops truncatus*) and common dolphins (*Delphinus delphis*). Bottlenose dolphins are known to engage in agonistic interactions with harbour porpoise around the British Isles, and these events can frequently lead to porpoise being killed by dolphins (Ross and Wilson, 1997). It would therefore not be surprising if porpoise were able to learn to avoid bottlenose dolphin whistles and clicks. In addition, bottlenose dolphins can hear NBHF clicks, and porpoise may therefore fall silent as an evasive strategy whenever they detect bottlenose dolphin whistles or clicks. However, whilst the frequent detection of delphinid vocalisation in our study may have been a driver of the low detection likelihood of porpoise clicks, in instances where sightings were made of dolphins during fieldwork operations, all identified species seen were common dolphins (which are known to frequent the area regularly in high numbers; Rogan et al. 2018).

It is also worth pointing out that detection ranges and likelihoods for NBHF clicks are expected to be much lower for porpoise than for delphinid clicks. This is because delphinid clicks are broadband and contain more omnidirectional low-frequency components that propagate over higher ranges. These low frequency (LF) components can also be detected when the dolphin is not directly echolocating at the SoundTrap. In contrast, porpoise clicks do not contain these LF components and can only be effectively detected when they point their echolcoation beam directly at the SoundTrap. In addition, the source levels of porpoise echolocation clicks are at least ~20 dB (factor 10 on a linear scale) lower than those of delphinid clicks (Villadsgaard et al. 2007) leading to a further reduction on detection likelihoods and ranges.

4.5 Application to regulators

An interesting question that arose when designing this study was under what circumstances eliciting a localised deterrence effect in non-predating endangered/protected/sensitive (EPS) species would be desirable from a conservations point of view? Dolphin and porpoise regularly get bycaught in static gillnets (Read et al. 2006), and the use of gillnet pingers is generally considered a successful mitigation method (Barlow & Cameron 2006). The design goal of the current TAST system has been to prevent disturbance in high-frequency hearing specialists that are listed as EPS species (Götz & Janik, 2015 & 2016). However, it would be possible to include a “gillnet pinger capability” to the current TAST signal to achieve mitigation of cetacean bycatch as well. For example, Figure 5 shows a minor harmonic of the TAST signals which has so far been supressed but could be enhanced to add mid-frequency components at lower TOB levels (SPL) that can be fine-tuned to cause a localised deterrence effect in delphinids and porpoise. This would be fundamentally different from just using a conventional ADD, which are known to cause large-scale habitat exclusion in cetaceans (Johnson 2020). The proposed “gillnet pinger capability” would involve (1) emitting the mid-frequency components at the source level (TOB) of an accepted gillnet pinger, while the main signal component (aiming to deter seals) would be emitted at a higher source level, and (2) the noise dose and duty cycle would remain as low as the current TAST system (1 to 2%). The TAST system could then effectively combine gillnet pinger and depredation reduction technology into a single signal and device. This has a significant advantage from a conservational point of view in that it would make the additional use of a pinger redundant, therefore reducing overall noise emissions. We recommend that regulators consider this, and open pathways for discussion for developing and using combined bycatch and predation reduction devices.

4.6 Conclusions

Sound signals from the TAST prototype were in line with factory calibration and dropped quickly with distance, indicating a highly localised deterrence effect that does not propagate over large areas. Whilst vocalisations of baleen whales were rare across both control and test nets (with only a handful of encounters identified), delphinid vocalisations were encountered frequently throughout the whole experimental period indicating regular presence of dolphins around the nets. Statistical analyses of these vocalisations provide clear evidence for a strong effect of diurnal cycle on delphinid vocalisation rates. Vocalisation rates of both whistles and BB clicks were much higher during the night compared to daylight hours. Statistical modelling suggests the presence of delphinids around fishing nets was unaffected by TAST operation with predicted detection likelihoods being similar during ON and OFF periods, and at control and test nets. Porpoise detections were rare, and whilst no evidence was found that porpoise presence was impacted by the operation/presence of the TAST, no definitive conclusions can be drawn. Low porpoise presence in the region could be related to broadscale decreases in populations, or an increased presence of delphinids. We make suggestions for regulatory frameworks to consider the option of using combined (TAST) devices that prevent lethal bycatch of delphinids and porpoise (causing a small-scale localised deterrence of these species) while also preventing depredation by phocid seals.

5. ACKNOWLEDGEMENTS

In addition to NPWS grant SPU G27-2021, work was funded via a Marie Sklodowska-Curie Actions (MSCA) Individual fellowship to SLC. Field-trials were also funded by the EMFAF Marine Biodiversity Scheme at the Marine Institute. Special thanks is given to the crew and skippers of the Realt na Mara and the Start of David, alongside scientific observers involved in data recording. Thanks to Dr Mark Jessopp for advice on experimental design. Special thanks to Dr Michele Cronin, who helped initiate the work.

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7. APPENDIX

7.1 Whistle & Moan Detector settings used for TAST and delphinid whistle detection

Table A1. PAMGuard Whistle & Moan Detector settings used for TAST and delphinid whistle detection.

Parameter	TAST detector	Whistle detector
FFT time resolution (ms)	10.7	10.7
Min frequency (kHz)	1.7	3.5
Max frequency (kHz)	2.2	30
Min length (steps)	20	20
Min total size (pixels)	20	20
Max cross length (steps)	5	5
Threshold (dB)	8.0	6.5

7.2 PAMGuard Click Detector settings used for echolocation click detection

Table A2. PAMGuard Click Detector settings used for echolocation click detection

Parameter	Click detector
Sample rate (kHz)	384
Pre-filter type, order	IIR Butterworth, 4
Pre-filter high pass (kHz)	5
Trigger filter type, order	IIR Butterworth, 6
Trigger filter high pass (kHz)	10
Min click separation (samples)	100
Max click length (samples)	1,024
Pre sample (samples)	40
Post sample (samples)	40
Long filter/short filter	1e-5/1e-1
Threshold (dB)	20.0

7.3 Table 1c

Table A3. PAMGuard Click Classification settings used for classification of candidate click detections

Parameter	Broadband low frequency (BB)	Narrowband high frequency (NBHF)
Test band (kHz)	15 – 120	110 – 150
Control band 1 (kHz)	0 – 10	0 – 100
Control band 1 threshold (dB)	15.0	20.0
Control band 2 (kHz)	140 – 180	160 – 180
Control band 2 threshold (dB)	15.0	5.0
Peak frequency range (kHz)	30 – 150	110 – 150
Peak width range (kHz)	30 – 100	---
Peak width threshold (dB)	5.0	---